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Greenhouse gas and ammonia emissions and mitigation options from livestock production in peri-urban agriculture: Beijing – A case study

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ABSTRACT

Livestock production in peri-urban areas constitutes an important sub-sector of the agricultural production system in China, and contributes to environmental degradation and local air borne pollution contributing to smog. As a result, local policies are being implemented to safeguard the environment. However, there has been little attempt to quantify the impact of environmental policies on livestock production structure, spatial distribution and their related greenhouse gases (GHGs) and ammonia (NH_3) emissions. Here, we calculated the inventories of GHGs and NH_3 emissions for 2010 and 2014 for peri-urban livestock production in Beijing, using reliable spatially explicit data, which was collected from 1748 industrial farms in 2010 and 2351 industrial farms in 2014, including pig, dairy, beef cattle, poultry and sheep farms. Our estimates indicated that total industrial livestock production increased by 17% between 2010 and 2014, even under the more strict environmental protection polices, with farm size decreasing by between 7% and 47%. Up to 50% of the industrial livestock farms have remained in operation, with the rest closing down or being moved to other regions. Following this trend, total GHGs emission decreased from 5.0 to 4.5 Tg CO_2-eq between 2010 and 2014. Most of the GHGs emission reduction was due to the lowering of energy related carbon dioxide (CO_2) emission in 2014. Total NH_3 emission decreased from 102 to 96 Gg between 2010 and 2014, mainly due to more stringent environmental regulations for new and extended farms (increased in farm size), e.g. Discharge standard for pollutants for livestock and poultry breeding. Our study identified that GHGs and NH_3 emission hotspots were concentrated in suburban areas (around the city centre and with less agricultural resource and population density) in 2010. However, between 2010 and 2014 these hotspots moved to the exurban plain and mountain area following the closure or sub-division of intensive farms in suburban regions and construction of new and small farms in exurban areas (around the suburban and with more agricultural resource and lower population density). Scenario analysis suggests that total GHGs emission can be reduced by up to 1.0 Tg CO_2-eq (23% of total livestock sector emissions) in Beijing, using a combination of modifications of farm type, livestock diet and manure management. The integrated scenario can reduce CH_4, N_2O and NH_3 emissions by 27%, 9% and 35%, compared to the reference scenario. Within this short period of time (5 years), policies have had direct impacts on peri-urban livestock production in Beijing, resulting in marked changes in the structure of different livestock sectors, as well as the GHGs and NH_3 emission inventories and their spatial distribution. Our analysis clearly shows that the success of these (and future) polices relies on optimizing spatial management of new livestock production systems. Policy and farmer guidance should focus on optimizing livestock diet and on-farm manure management, industrial production systems and the pig and poultry sectors in peri-urban regions.

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1. Introduction

Rapid development of urban agriculture is associated with greenhouse gases (GHGs) and ammonia (NH_3) emissions and climate change (Broto and Bulkeley, 2013). Global atmospheric concentrations of the most important gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and ammonia (NH_3) have increased significantly in the last 150 years (Monteny et al., 2006; IPCC, 2014). Livestock farming systems are major source of trace gases contributing to atmospheric pollution locally and globally. The greenhouse gas emissions of livestock production and its by-products accounted for 18% of global total emissions (IPCC, 2014; Appuhamy et al., 2016). The 2nd National Climate Change Information Bulletin of China estimated that greenhouse gas emissions from agricultural activities was about 819 Tg of CO_2-eq, and that enteric fermentation and manure management contributed 54% of total agriculture GHGs emission (MNDFC, 2013). Therefore, gaseous emissions from livestock production must be better quantified to provide underpinning evidence for country- and regionally-specific inventory compilation, and for the prioritisation of mitigation strategies.

An urban livestock system is characterized by a large variation of livestock production systems that occur in and around densely populated areas and that strongly interact with the surrounding. Due to certain conditions, e.g., higher human population density, higher demand for livestock products, and increased industrialization and urbanization, the environmental impact of peri-urban livestock production has become more significant (Chadwick et al., 2015; Ma et al., 2014a, 2014b). During the period of 12th Five-Year plan (2011–2015), agricultural pollution sources were incorporated into the total control management system of China. Within this, large scale intensive livestock farms and collective feedlots have become the main focus for targeted mitigation. Meanwhile, some studies have shown high losses of nutrients around large cities (Shao et al., 2006; Ma et al., 2012), and that manure may need to be exported from peri-urban areas in the future to limit the effects on the environment, if livestock production continues to grow (Jia et al., 2015). Therefore, there is a need to focus more on characteristics of urban livestock production and its impact on the urban environment. In the last decade, many studies have reported on GHGs emission from livestock production based on national statistical data, and individual farm data (Garnett, 2007, 2009; Nguyen et al., 2010; Lesschen et al., 2011; Weiss and Leip, 2012; Bellarby et al., 2013; Appuhamy et al., 2016; Owen and Silver, 2015). However, due to limited availability of information from livestock systems at the farm- and regional level, accurate and quantitative GHGs and NH_3 inventories are scarce (Liang et al., 2013). Therefore, it is of great importance to quantify the GHGs and NH_3 emission of livestock production systems in urban and peri-urban areas, and to understand the spatial and temporal dynamics of these gaseous emissions.

Hence, the aim of this study was to quantify the changes in gaseous emissions from livestock farms in peri-urban areas of a rapidly growing city. We used Beijing as a case study, using the data collected from 1748 farms in 2010 and 2351 farms in 2014, to highlight the hotspots of GHGs and NH_3 emission and to estimate the potential of various mitigation strategies in peri-urban livestock production in the future. Scenario analysis was based on empirical data and modelling. In Beijing, livestock production in the urban center area is prohibited, however peri-urban livestock production is common. So there is no livestock production in urban center area. Therefore, although we have studied urban livestock in this paper, it is actually the study of peri-urban livestock production. Specific objectives were:

(1) to generate inventories of gaseous emissions (CH_4, CO_2, N_2O and NH_3) from large livestock production systems in the peri-urban area of Beijing during a period when environmental policies were introduced (2010–2014);
(2) to understand the spatial and temporal dynamics of gaseous emissions (CH_4, CO_2, N_2O and NH_3) from livestock production and highlight the hotspots of emission in peri-urban areas;
(3) to evaluate the potential of various mitigation measures and policy options for decreasing gaseous emissions from peri-urban livestock production systems.

2. Material and methods

2.1. System boundary

The system boundary of this research covered the production processes from “cradle” to “farm-gate” of livestock production systems, and the total GHGs emission include: (1) Feed production and processing: direct and indirect emission of N_2O in the process of N fertilizer manufacture and following application for feed production; NH_3 emission from N fertilizer application; fossil fuel CO_2 emissions from the manufacture of plastic sheeting and pesticides, and application of urea during feed production, machinery use during feed production, such as ploughing, seeding and harvesting; (2) CH_4 emission from enteric fermentation and manure treatment; direct and indirect N_2O emission from the manure management chain (housing, manure storage and treatment); CO_2 emissions from energy generation and consumption during animal production, such as electricity, coal, gasoline; (3) direct and indirect emission of N_2O from manure applications to cropping land (after manure has left the livestock farm); CO_2 emission through energy consumption during manure application (Fig. 1).

The study area is the capital of China – Beijing city. The whole Beijing city is divided into an urban center area (zone 1) and a peri-urban area. Peri-urban areas comprise three parts: the suburban area (zone 2), exurban plain area (zone 3) and exurban mountain area (zone 4) (Fig. 2). In total, seven animal categories were considered: pig, dairy, beef cattle, layer, broiler, duck and sheep. For each animal category, four farm classes were distinguished, namely traditional farming households, small farms, medium farms and intensive farms (SI). The traditional farming households produced animal feed themselves on their own land, and the industrial farms (small, medium and intensive farms) were landless, so all the feed was purchased from off-farm sources. Small household farms were more wide spread through the whole of Beijing except the urban center, and most of them were not regulated by policy, and not registered in the monitoring system. However, the industrial livestock production systems were registered in the system and more influenced by the policy. In this study, there were 1748 industrial

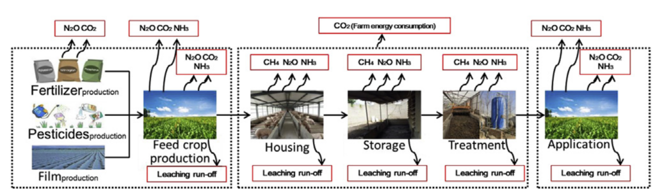

Fig. 1. Illustration of the system boundary used in this study. The emission from feed production, housing, manure storage and manure treatment, the key stages of animal production systems. Emissions inside of the dotted line are the local GHGs (CH_4, CO_2 and N_2O) and NH_3 emission for Beijing. Emission outside of the dotted line are the external GHGs and NH_3 emissions.

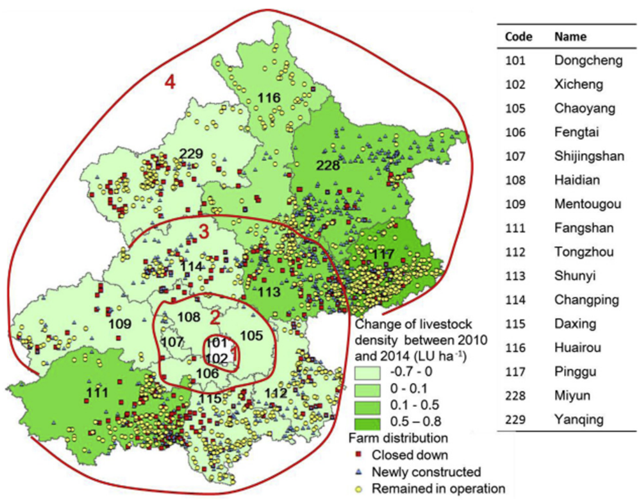

Fig. 2. Changes in livestock density of Beijing and the distribution of intensive livestock farms in 2014. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Source: Beijing Statistical Yearbook. Changes between 2010 and 2014 are indicated by different colored symbols: red squares = industrial livestock farms from 2010 that had 'disappeared' by 2014; blue triangles = new industrial livestock farm that 'appeared' in 2014; yellow dots = industrial livestock farm in 2010 that were still operating in 2014. The area inside zone (1) is the urban centre, and the area between zone (1) and (2) is the suburban area. The area between zones (2) and (3) is the exurban plain area, and the area between zones (3) and (4) is the exurban mountain area, respectively, according to government documents.

farm (728 pig farms, 239 dairy farms, 25 beef cattle farms, 307 layer farms, 291 broiler farms, 114 duck farms and 44 sheep farms) recorded for 2010, and 2351 industrial farms (961 pig farms, 231 dairy farms, 38 beef cattle farms, 479 layer farms, 492 broiler farms, 80 duck farms and 70 sheep farms) recorded for 2014 (Table 1). In 2010, there were 10 farms (3 small farms, 6 medium farms and 1 intensive farm) in the suburban area, 734 farms (240 small farms, 408 medium farms and 86 intensive farms) in the exurban plain area and 1006 farms (380 small farms, 547 medium farms and 79 intensive farms) in the exurban mountain area. By 2014, numbers had changed to 2 farms (0 small farms, 2 medium farms and 0 intensive farm) in the suburban area, 922 farms (349 small farms, 464 medium farms and 109 intensive farm) in the exurban plain area and 1427 farms (609 small farms, 749 medium farms and 69 intensive farm) in the exurban mountain area. We used the survey data to calculate GHGs and NH_3 farm gate emissions from the industrial livestock farms, using the method of Wei et al. (2016). The survey was continued from 2011 to 2013 including 92 pig farms, 28 dairy farms, 11 beef cattle farms, 27 layer farms, 26 broiler farms, 17 duck farm and 11 sheep farms which was used to gain the emission factors of different farm size (animal number of the farm) (Wei et al., 2016). The emissions evaluation was carried out for each farm in both years (2010 and 2014). Next, we estimated emissions from the small traditional farming households using statistical data, based on livestock populations and appropriate emission factors (Wei, 2016). The number of livestock in traditional farming households was corrected according to the total livestock number minus the livestock numbers in the industrial farms.

2.2. Calculation of gaseous emissions

In this study, total GHGs emission included 'local' GHGs emission and 'external' GHGs emissions. The so called 'local' GHGs emission included GHGs emission from locally supplied feed production and livestock production. However, GHGs from electricity consumption was not included, since there are no power plants in the Beijing area now. The 'external' GHGs emissions were calculated as the difference between total GHGs emission and 'local' GHGs emission, which happened outside of Beijing city. Detailed calculations are shown below and in the supplementary information (SI) (Table S1).

2.3. Gaseous emission from feed production

The gaseous emissions from N fertilizer applied to animal feed production are mainly in the form of N_2O, including direct and indirect emissions. The indirect N_2O emission included the N_2O emission from atmospheric deposition by NH_3 and NO_x and from N leaching and runoff. Formula (1) was applied to calculate the N_2O emission from feed production by N fertilizer use (IPCC, 2006). The calculation of direct and indirect emission from feed consumption are shown in SI (Table S1)

$$GE_{feed\ \ N_2O} = GE_{feed\ \ dir\ \ N_2O} + GE_{feed\ \ indir\ \ N_2O} \tag{1}$$

where $GE_{feed\ N_2O}$ is the N_2O emission from feed consumption; $GE_{feed\ dir\ N_2O}$ and $GE_{feed\ indir\ N_2O}$ are N_2O direct and indirect emissions from feed consumption, respectively.

The calculation of other gaseous emissions, e.g. NH_3 emission from N fertilizer application and CO_2 emission from urea fertilizer use, are shown in SI (Table S1) (IPCC, 2006).

Formula (2) was used to calculate the gas emissions resulting from feed production, including emissions associated with machinery, irrigation, film and pesticides use (Huang, 2015). The calculations of CO_2 emission from machinery, irrigation, film and pesticide are shown in SI (Table S1–S4).

$$GE_{feed\ \ CO_2} = GE_{feed\ \ machine\ \ CO_2} + GE_{feed\ \ irrig\ \ CO_2} + GE_{feed\ \ film\ \ CO_2} + GE_{feed\ \ pest\ \ CO_2} \tag{2}$$

where $GE_{feed\ CO_2}$ is the CO_2 emission from feed production; $GE_{feed\ machine\ CO_2}$, $GE_{feed\ plast\ CO_2}$, $GE_{feed\ pest\ CO_2}$ are the CO_2 emissions from using machinery, irrigation, plastic and pesticides for feed production.

2.4. Gaseous emissions from enteric fermentation

The CH_4 emission from enteric fermentation in ruminant (e.g. dairy, beef cattle and sheep) and non-ruminant (pigs) livestock were included in this study and calculated by formula (3). Methane emission from enteric fermentation is directly linked to the number of animals, using Tier 2 emission factors (IPCC, 2006). The emission factors for CH_4 ($EF_{enteric\ CH_4}$, kg CH_4 head^{-1} yr^{-1}) were determined as function of gross energy intake (GE_{intake}, MJ head^{-1} yr^{-1}) and the CH_4 conversion factor (Y_m, % of GE) which was calculated by formula (4) (Hou et al., 2016). The energy content of CH_4 was defined as 55.65 MJ kg^{-1} CH_4 (IPCC, 2006).

$$GE_{enteric\ \ CH_4} = \mathrm{NUM}_{animal} \times \mathrm{EF}_{enteric\ \ CH_4} \tag{3}$$

$$EF_{enteric\ \ CH_4} = GE_{intake} \times Y_m/55.65 \tag{4}$$

where, $\mathrm{GE}_{enteric\ CH_4}$ is the CH_4 emission from enteric fermentation; NUM_{animal} is animal number.

2.5. Gaseous emissions from manure management

Emissions from farm manure management are challenging to

Table 1
Changes in intensive animal farms in Beijing between 2010 and 2014.

Animal	Year	Farm number	Animal number (10^3 head)	Farm size (head farm^{-1})			
				Average	Small farm/total farm	Medium farm/total farm	Intensive farm/total farm
Pig	2010	728	1319	1811	34%	64%	2%
	2014	961	1937	2014	37%	60%	3%
Remained of farm number		526 (56%)					
Changes of farm number		233 (32%)					
Changes of animal number			618 (47%)				
Changes of farm size				203 (11%)			
Dairy	2010	239	161	671	43%	36%	21%
	2014	231	163	705	51%	29%	20%
Remained of farm number		165 (71%)					
Changes of farm number		−8 (−3%)					
Changes of animal number			2 (1%)				
Changes of farm size				34 (5%)			
Beef cattle	2010	25	24	976	20%	48%	32%
	2014	38	34	885	50%	29%	21%
Remained of farm number		18 (47%)					
Changes of farm number		13 (52%)					
Changes of animal number			10 (42%)				
Changes of farm size				−91 (−9%)			
Layer	2010	307	12,571	40,949	29%	62%	9%
	2014	479	16,965	35,418	43%	50%	7%
Remained of farm number		206 (43%)					
Changes of farm number		172 (56%)					
Changes of animal number			4394 (35%)				
Changes of farm size				−5531 (−14%)			
Broiler	2010	291	12,467	42,842	34%	54%	13%
	2014	492	19,510	39,734	35%	58%	7%
Remained of farm number		204 (42%)					
Changes of farm number		201 (69%)					
Changes of animal number			7043 (56%)				
Changes of farm size				−3108 (−7%)			
Duck	2010	114	7853	71,386	53%	33%	14%
	2014	80	4150	57,640	55%	36%	9%
Remained of farm number		28 (35%)					
Changes of farm number		−34 (−31%)					
Changes of animal number			−3703 (−47%)				
Changes of farm size				−13746 (−19%)			
Sheep	2010	44	62	1400	50%	20%	30%
	2014	76	56	740	55%	16%	29%
Remained of farm number		21 (28%)					
Changes of farm number		16 (36%)					
Changes of animal number			−6 (−10%)				
Changes of farm size				−660 (−47%)			

Note: Small farms for pig, dairy, beef cattle, layer, broiler, duck and sheep comprise livestock numbers of <1000, <500, <500, <10,000, <10,000, <10,000 and <500, respectively. Medium farm for pig, dairy, beef cattle, layer, broiler, duck and sheep comprise livestock numbers of 1000–9999, 500–999, 500–999, 10,000–99,999, 10,000–99,999, 10,000-99,999 and 500–999, respectively. Intensive farms for pig, dairy, beef cattle, layer, broiler, duck and sheep comprise livestock numbers of ≥10,000, ≥1000, ≥1000, ≥100,000, ≥100,000, ≥100,000 and ≥1000, respectively.

measure and model due to the variability in management systems. Hence, in this study we calculated the gaseous emissions from the different stages of the manure management system, i.e. housing, storage and treatment processing (Wei et al., 2016) using formulas (5) to (7). The calculations for NH_3, N_2O and CH_4 emission from the housing, storage and manure treatment stages of the manure management chain were taken from Wei et al. (2016) and Hou et al. (2017). $EF_{manure\ \ N_2Oj}$, $EF_{manure\ \ NH_3j}$ for different livestock categories of different farm size are shown in Table S5.

$$GE_{manure\ \ N_2O} = EF_{manure\ \ N_2Oj} \times N_{manurej} \times \frac{44}{28} \tag{5}$$

$$GE_{manure\ \ NH_3} = EF_{manure\ \ NH_3j} \times N_{manurej} \times \frac{17}{14} \tag{6}$$

$$GE_{manure\ \ CH_4} = EF_{manure\ \ CH_4j} \times C_{manurej} \times \frac{16}{12} \tag{7}$$

where $EF_{manure\ \ N_2Oj}$, $EF_{manure\ \ NH_3j}$ and $EF_{manure\ \ CH_4j}$ are N_2O, NH_3 and CH_4 emission factors from different procession of manure management. $N_{manurej}$ and $C_{manurej}$ are the quantities of manure N and C before entering the different processes. The calculations of $N_{manurej}$ and $C_{manurej}$ were expressed in SI.

2.6. Gaseous emissions from manure application

The gaseous emissions caused by manure applied to cropping systems are mainly in the form of N_2O, including direct and indirect emissions. The indirect N_2O emission included the N_2O emission from atmospheric deposition by NH_3 and NO_x and from N leaching and runoff (IPCC, 2006). Formula (8) was applied to calculate the gaseous emissions from manure application to land, and the calculations of direct and indirect N_2O emission from manure land applied are shown in SI (Table 1).

$$GE_{land\ \ N_2O} = GE_{land\ \ dir\ \ N_2O} + GE_{land\ \ indir\ \ N_2O} \tag{8}$$

where $GE_{land\ N_2O}$ is the N_2O emission from manure application; $GE_{land\ dir\ N_2O}$ and $GE_{land\ indir\ N_2O}$ are N_2O direct and indirect emissions from manure application, respectively.

Formula (9) was applied to calculate the NH_3 emissions from manure application to land.

$$GE_{land\ \ NH_3} = N_{manure\ \ application} \times F_{NH_3} \times \frac{17}{14} \tag{9}$$

where F_{NH_3} is the N emission factors of manure applied to crop, which were 19% for F_{NH_3} (Velthof et al., 2009).

2.7. Gaseous emissions from energy consumption in livestock farm

The energy consumption in livestock farms can be divided into several categories: energy consumption of mechanical and transport equipment; energy consumption of the environmental control equipment and other facilities such as the consumption of coal by boilers, natural gas and other energy sources. There is no detailed classification of energy consumption values, so here we used emission factors for different farm types (Huang, 2015). Formula (10) was applied to calculate the energy consumption.

$$GE_{energy\ \ CO_2} = \sum NUM_{animal} \times SC_{energy_n} \times EF_{energy_n} \tag{10}$$

where $GE_{energy\ CO_2}$ is the GHGs emission from farm energy consumption, in t CO_2 yr^{-1}; SC_{energy_n} is different energy consumption per livestock, in t energy $head^{-1}$ yr^{-1}, which was energy consumption per animal divided by the unit price of energy (Table S6); EF_{energy_n} is the emission factor for different energy, in t CO_2 (t $energy)^{-1}$, where energy included diesel oil and electric (Table S3).

2.8. Description of scenarios

Three scenarios were used to explore the potential for reducing GHGs and NH_3 emissions from different farm types and manure management chains, and compared with the business as usual (BAU) situation.

S0 – Business as usual (BAU). As the baseline scenario, the farm type and manure management was set at the current (2010) situation. The intensification rate of pig, dairy, beef cattle, layer, broiler, duck and sheep were 70%, 72%, 63%, 80%, 99%, 97% and 50%, respectively. Here, the intensification rate means proportion of the livestock number of >500 heads per pig farm, >200 heads per dairy cows, beef cattle and sheep farm, and >2000 heads per laying hens, broiler and duck, of the total livestock number. The feed conversion rate and feed composition was shown at Tables S7–S13.

S1 – Increased intensification rate. This scenario builds on S0. In S1, we increased the intensification rate by 10%, 10%, 35%, 10%, 1%, 3% and 20%, compared to S0. We assumed that the total livestock number in Beijing remained constant, and the mean farm size increased 40% while the number of small household farm (pig farm <500 head, dairy, beef cattle and sheep farm <200 head, layer farm <5000 head, and poultry farm <10,000 head) decreased.

S2 – Optimized livestock diet and herd management. This scenario builds on S0. In S2, the diets for different livestock were optimized (e.g. via a reduction in crude protein intake and use of synthetic amino acids) and the herd management was also optimized (e.g. enhanced care of weaning pigs to reduce the mortality rate and requirement for sows) to reach the EU average feed conversion ratio (FCR). For example, the quantity of pig feed was reduced by 18.5% without feed composition change, equivalent to the FCR in EU of 2.9 kg feed (kg carcass $weight)^{-1}$ (Hyun and Ellis, 2002). Similarly, the quantity of dairy feed was reduced by 18.0% through adopting precision feeding and better herd management, equivalent to the feed conversion ratio (FCR) in EU (0.9 kg feed (kg $milk)^{-1}$) (Garg et al., 2013). The quantity of beef cattle and sheep feed was reduced by 39.0% through use precision feeding and better herd management, equivalent to the FCR in EU (6.5 kg feed (kg $beef)^{-1}$) (Fernandes et al., 2014; López-Campos et al., 2013). The quantity of layer feed was reduced by 6.0%, through use precision feeding and better herd management, equivalent to the FCR in EU (1.9 kg feed (kg $eggs)^{-1}$) (Pérez-Bonilla et al., 2012). Also, the quantity of broiler and duck feed was reduced by 10.0%, through use precision feeding and better herd management, equivalent to the FCR in EU (1.8 kg feed (kg $meat)^{-1}$) (Sutton et al., 2011).

S3 – Improved manure management. Builds on S0, we assumed that the GHGs (CH_4, CO_2 and N_2O) and NH_3 losses (in % of excreted N) from the farm system (livestock housing, manure storage and manure treatment) will decrease by adopting best management practices to minimize emissions for different livestock categories. These gaseous emission reductions will be achieved via e.g. optimizing the housing type (e.g. floor type), manure storage strategies (e.g. cover or uncover, underground or over ground), and manure processing (anaerobic digestion and composting) (Wei et al., 2016; Wei, 2016). Details were shown in Table S7.

S4 – Combination of S1, S2 and S3. In this scenario, the measures of S1, S2 and S3 are combined. On the basis of increased intensification rate in S1, we reduced feed protein inputs in S2 and chose the best manure management to reduce the emission.

3. Results

The changes in industrial livestock farms between 2010 and 2014 are shown in Table 1. Total livestock production expanded between 2010 and 2014, even under the more strict environmental regulations. The number of industrially reared pigs increased by 47%, and livestock numbers also increased by 1% for dairy cows, 42% for beef cattle, 35% for laying hens and 56% for broiler chickens. However, the number of ducks and sheep decreased by 47% and 10%, respectively, during the same period. Interestingly, the average farm size decreased for most of the animal categories in these five years, except for pigs and dairy cows. This was because the number of small size livestock farms has expanded quickly, while the number of medium and intensive farms has remained relatively constant. Hence, the proportion of small farms has increased, and the average farm size has decreased (Table 1).

The temporal and spatial variation of livestock farms from 2010 to 2014 reveals that only 50% of farms have remained in operation, with the remaining 50% closed down or sub-divided into several small size farms (Fig. 2). Of all the livestock sectors dairy farms remained more consistent in terms of their size and livestock numbers, with around 71% of farms staying in production between 2010 and 2014, followed by pig farms (56%), beef cattle farms (47%) and poultry farms (Table 1). Fig. 2 also indicates that livestock farms became more centralized around the peri-urban areas of the city between 2010 and 2014, with livestock numbers increasing markedly in exurban areas but decreasing in suburban areas.

3.1. Temporal and spatial variation of gaseous emission hotspots

GHGs emission (CO_2-eq) from livestock production in the peri-urban area of Beijing for 2010 and 2014 are shown in Fig. 3. Total GHGs emission was 5.0 Tg CO_2-eq in 2010, and decreased to 4.5 Tg CO_2-eq in 2014, i.e. a decrease of 12% the in five years. The temporal and spatial variation of local GHGs emission, expressed as CO_2-eq, from livestock production in peri-urban area of Beijing for 2010 and 2014 are shown in Fig. 4. The local GHGs emissions patterns have changed from scattered sources to hotspots of emission as a result of the changes in livestock sector structures. The reason is the

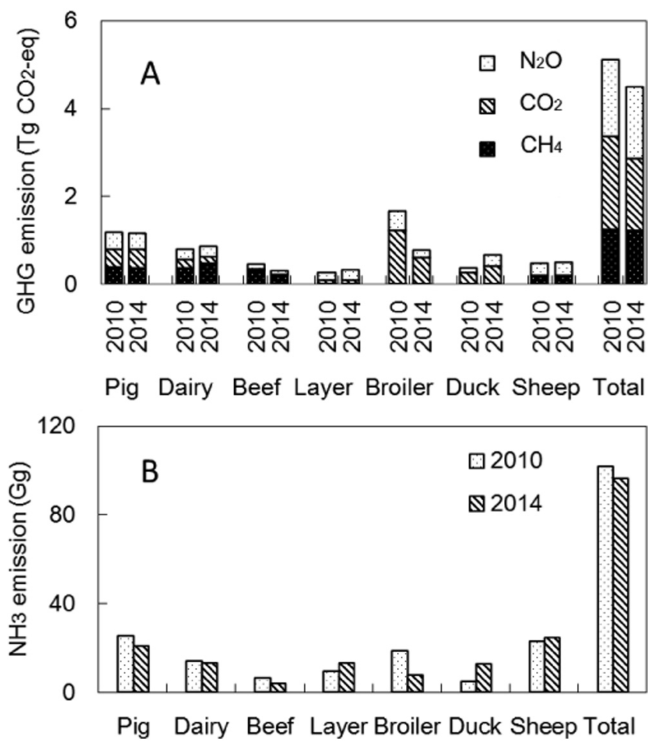

Fig. 3. GHGs (Tg CO_2-eq) and NH_3 emission (Gg) from livestock production in peri-urban area of Beijing for 2010 and 2014. CO_2-eq calculated using GWP: 298 for N_2O and 25 for CH_4.

decrease in local feed production emission due to the increased intensification rate (proportion of the livestock number in the farms where farm size large than 500 heads for pig, 200 heads for dairy cattle, beef cattle and sheep, and 2000 heads for laying hen, broiler and duck, to the total livestock number of each animal category). The hotspots were initially (2010) more concentrated in southeast suburban and exurban plain areas, but transferred to exurban mountain areas in 2014. The largest increases in emissions appeared in the north exurban mountain area where many pig, dairy and broiler farms have been either newly constructed or rapidly expanded.

The temporal and spatial variation of NH_3 emissions from livestock production in peri-urban area for 2010 and 2014 are shown in Figs. 3 and 5. Total NH_3 emissions from all livestock production decreased from 102 Gg in 2010 to 96 Gg in 2014, a decrease of 6%. The changes of local NH_3 emission hotspots were similar to the GHGs emissions, i.e. a change from 'scattered' emissions to concentrated hotspots in the past five years. The reason is also the decrease in local feed production emissions due to the increased intensification rate. The hotspots were more concentrated in southeast exurban plain areas, and hotspots transferred to exurban mountain areas in 2014 compared with 2010. Again, the largest increases in emissions appeared in north exurban mountain are where new pig and layer farms have been constructed. The hotspots around drinking water sources, e.g. the Miyun reservoir in exurban mountain area have gradually reduced due to the regulation "Measures for the Administration of Pollution Prevention and Control of Livestock and Poultry" which prohibited livestock farm around the drinking water source.

3.2. Comparison of GHGs and NH_3 emission of different animal category

The GHGs and NH_3 emission per kg of different animal product are shown in Table 2. These footprints include embedded emissions from feed and fertilizer used to grow feeds, and direct and indirect emissions from the housing, manure storage, manure processing, and spreading of manure and fertilizer on cropping land. The GHGs emission per kg product all decreased in 2014 compared with 2010. Sheep production had the highest GHGs emission as 25.2 kg CO_2-eq per kg product in 2014, followed by beef cattle (14.4 kg CO_2-eq per kg product), pig (3.7 kg CO_2-eq per kg product) and broiler (3.5 kg CO_2-eq per kg product) in 2014. Dairy had the lowest GHGs footprint which was 1.3 kg CO_2-eq per kg liquid milk in 2014. The CO_2-eq per kg product in 2014 was lower than that in 2010 for all the livestock products.

The NH_3 emission per kg product also decreased in 2014 compared with 2010 (Table 2). Sheep production had the highest NH_3 emission as 1028 g NH_3 per kg meat product in 2014, followed by beef cattle (207 g NH_3 per kg product), pig (67 g NH_3 per kg product) and layers (62 g NH_3 per kg eggs) in 2014. CH_4 and NH_3

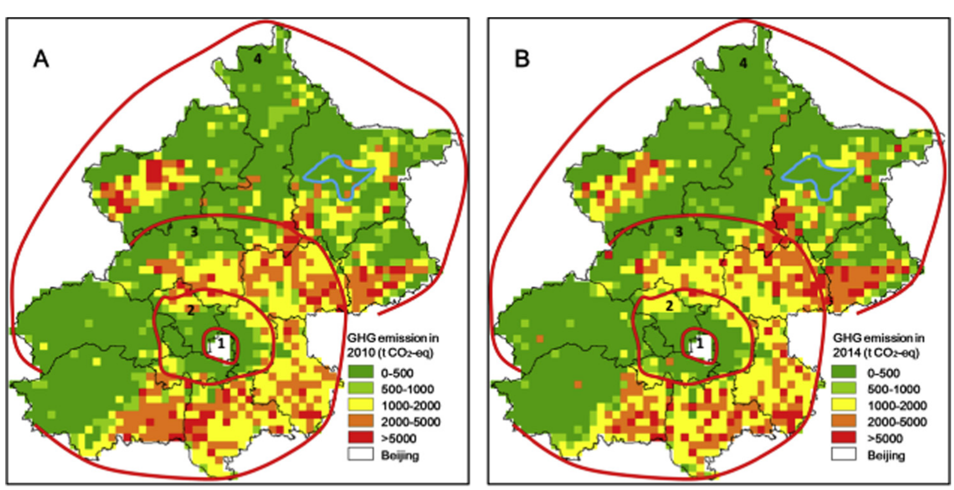

Fig. 4. Temporal and spatial variations of local GHGs emission from livestock production in the peri-urban area of Beijing in 2010 (A) and 2014 (B). CO_2-eq calculated using GWP: 298 for N_2O and 25 for CH_4. The area inside zone (1) is the urban centre, and the area between zones (1) and (2) is the suburban area. The area between zones (2) and (3) is the exurban plain area, and the area between zones (3) and (4) is the exurban mountain area, respectively, according to governmental documents. The blue circle is the main drinking water source (Miyun reservoirs). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

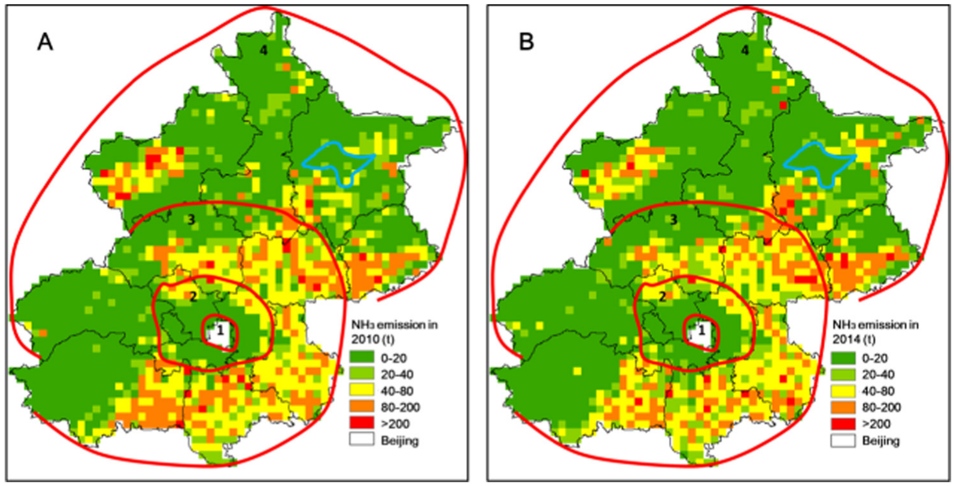

Fig. 5. Temporal and spatial variations of NH_3 emission from livestock production in the peri-urban area of Beijing in 2010 (A) and 2014 (B). The area inside zone (1) is the urban centre, and the area between zones (1) and (2) is the suburban area. The area between zones (2) and (3) is the exurban plain area, and the area between zones (3) and (4) is exurban mountain area, respectively, according to governmental documents. The blue circle is the main drinking water source (Miyun reservoirs). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

emissions were negatively related to farm size due to the more effective manure treatment on industrial farms, while N_2O and CO_2 emissions increased with increasing farm size due to the high energy consumption in industrial farms (except the N_2O emission by the poultry production system), when expressed per unit of animal product (Table S15).

3.3. Gaseous emission inventories for livestock production in a peri-urban area

The GHGs and NH_3 emission inventories of livestock production in 2010 and 2014 are shown in Fig. 3. The total CO_2, N_2O and CH_4 emissions from livestock production in Beijing were 2.1, 1.7 and 1.2 Tg CO_2-eq in 2010, which then decreased to 1.6, 1.6 and 1.2 Tg CO_2-eq in 2014, respectively. In 2010, CO_2 emission constituted the largest proportion of the total GHGs emission (42%), followed by N_2O emission (34%) and CH_4 emission (24%). In 2014, CO_2 emission constituted the largest proportion of the total GHGs emission (36%) followed by N_2O emission (37%) and CH_4 emission (27%).

The largest contribution to the GHGs emissions was broiler production (32% of total GHGs emission) in 2010, and pig production (25% of the total emissions) in 2014, respectively (Fig. 3). The relative contribution of duck and layer farms in 2014 increased by 108% and 43% compared with 2010, and the relative contribution of broiler and beef cattle decreased by 47% and 28% compared with 2010, due to the large changes in farm size.

With regard to NH_3 emission, sheep contributed the largest proportion of the emission (25 $Gg\ yr^{-1}$, equal to 25% of the total NH_3 emission), followed by emissions from pig (21 $Gg\ yr^{-1}$, equal to 22% of the total NH_3 emission), dairy (13 $Gg\ yr^{-1}$, equal to 14% of the total NH_3 emission) and layer farms (13 $Gg\ yr^{-1}$, equal to 13% of the total NH_3 emission) in 2014 (Fig. 3). In 2014, the relative contribution of broiler and beef cattle farms to NH_3 emissions decreased by 58% and 42% compared with 2010, and the relative contribution from duck and layer farms increased by 168% and 41% compared with 2010. This is a result of lower emission factors from industrial systems (Table S5).

Exploration of the GHGs emission from the different parts of the food production chain show that feed production and processing are responsible for the greatest contribution (39%) to total emissions for layer production (Table 3). Enteric fermentation was the largest source of GHGs emission (58%) for beef cattle production, and was also responsible for the largest source of GHGs emission (47%) from dairy production. Manure management was the largest

Table 2
GHGs and NH_3 emissions per kg product[b] of livestock production in peri-urban area of Beijing in 2010 and 2014.

	Year	CH_4 (g CH_4)	N_2O (g N_2O)	CO_2 (kg CO_2)	CO_2-eq[a] (kg CO_2-eq)	NH_3 (g NH_3)
Pig	2010	44.8	4.3	1.9	4.3	71.1
	2014	44.6	3.9	1.5	3.7	66.7
Dairy	2010	21.1	1.1	0.3	1.6	22.1
	2014	27.6	1.1	0.2	1.3	21.9
Beef cattle	2010	364.0	15.3	1.2	14.6	212.3
	2014	366.0	13.6	1.2	14.4	207.0
Layer	2010	1.9	4.0	0.4	1.6	61.9
	2014	2.2	3.7	0.3	1.4	62.0
Broiler	2010	1.9	2.9	2.6	3.5	37.7
	2014	2.0	2.7	2.7	3.5	36.6
Duck	2010	2.8	3.8	2.0	3.2	41.2
	2014	2.8	3.5	2.1	3.2	41.0
Sheep	2010	339.6	54.3	1.5	25.7	1031
	2014	340.1	52.9	1.4	25.2	1028

[a] CO_2-eq calculated using GWP: 298 for N_2O and 25 for CH_4.
[b] Per kg carcass weight for pig, beef cattle, broiler and sheep; per kg liquid milk for dairy and per kg eggs for layer.

source of GHGs emission for both sheep (36%) and pig production (34%). Farm energy consumption makes the greatest contribution to total GHGs emission for poultry production, accounting for 72% for broiler and 58% for duck total emissions.

With regard to the different GHGs, the highest emission was CO_2 (associated with energy use in maintaining temperature and lighting) for poultry (broiler and duck) and pig production, accounting for 77%, 67% and 37% of their total GHG emissions, respectively. N_2O emissions contributed most to layer and sheep production, accounting for 77% and 60% of their total emissions, respectively. CH_4 contributed the most to beef cattle and dairy production, with 65% and 54% of the total emissions, respectively (Table 3).

3.4. Scenario analysis of gaseous emissions

The total GHGs mitigation potential from the livestock sector in Beijing ranged between 0.5 and 1.0 Tg CO_2-eq, equivalent to a 12–23% reduction of total Beijing livestock sector emissions in 2014 (Fig. 6). Overall GHGs emissions were significantly reduced (by 18%) in scenario 2 (optimizing livestock diet), and in scenario 4 (by 23%) (the combination of S1, S2 and S3) compared to the business as usual scenario (S0). A small increase of GHGs emission was observed for pig production in scenario 1 (increased by 2.0%). Of the single mitigation strategies, scenario 2 is more effective than S1 and S3 (improved manure management) in reducing GHGs emission, whilst S3 is more effective than S1 and S2 in reducing NH_3 emission.

Methane emissions can be reduced by 19%, N_2O emissions by 19%, CO_2 emissions by 2%, and NH_3 by 16% through the adoption of optimized livestock diets. The integrated option (S4) is more effective than the single mitigation options, both in optimizing livestock diet and herd management (S2) and reducing manure GHG losses (S3). In the combined scenario (S4), CH_4, N_2O and NH_3 can be reduced by 27%, 9% and 35%, respectively, compared with emission in the business as usual (S0) scenario.

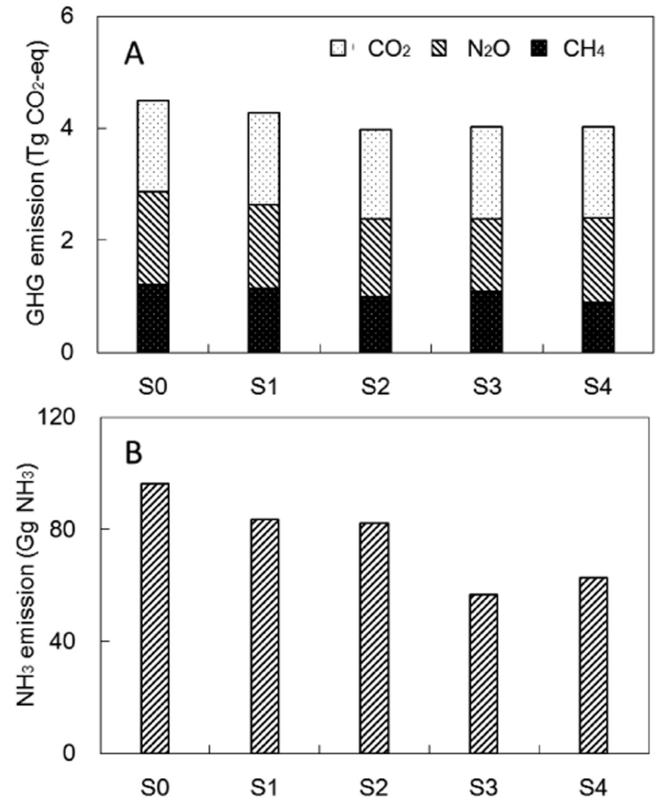

Fig. 6. Total GHGs and NH_3 emissions and mitigation potential in different scenarios (S0: business as usual. S1: improved farm size; S2: optimized feed diet; S3: improved manure management; S4: combination of S1, S2 and S3). CO_2-eq calculated using GWP: 298 for N_2O and 25 for CH_4.

4. Discussion

In this study, we characterized the GHGs (CH_4, N_2O CO_2) and NH_3 emissions from feed production, enteric fermentation, livestock housing, manure storage, manure processing, manure application and energy consumption in the peri-urban area of Beijing, and quantified the impacts of increased intensification rate, improved diet and manure management on GHGs and NH_3 mitigation. Our study highlights the temporal and spatial variation of livestock farm in peri-urban area. Also, with increased urbanization, the area of cultivated land has decreased rapidly and has been replaced by a high density of urban livestock farms, resulting in a large increase in external emissions, a significant increase in energy consumption by farm and feed production processing, and a rapid decrease in local emissions by feed and manure management. Scenario analyses suggest that optimizing livestock diet can be more effective than scenario 1 (increased intensification rate) and scenario 3 (improved manure management) in reducing GHGs emission as single options, whilst improving manure management is more effective than intensification rate and improved livestock diet in reducing NH_3 emission. The results of this study indicate that future research, policy and farmer guidance should focus on key strategies (optimizing livestock diet and on-farm manure management), industrial production systems and the pig and poultry sectors.

4.1. Comparison with other emission estimates

The United Nations Food and Agriculture Organization (FAO) divided the whole livestock production processing into two stages: i) the production process from “cradle” to “farm-gate”, including

Table 3
GHGs emissions inventories for different stage of livestock production, expressed in % of total.

Animal category	Feed product	Enteric fermentation	Manure management	Farm management	Land use	[a]CH_4	[a]N_2O	[a]CO_2
Pig	26	5	34	29	6	31	32	37
Dairy	10	47	25	12	6	54	28	18
Beef cow	25	58	14	0	3	65	27	8
Layer	39	0	35	6	20	4	77	19
Broiler	17	0	8	72	4	1	22	77
Duck	26	0	11	58	5	2	32	67
Sheep	16	32	36	1	17	34	60	6

[a] CO_2-eq calculated using GWP: 298 for N_2O and 25 for CH_4.

GHGs emission caused by the production and processing of feed, storage and treatment of manure, enteric fermentation and transport, energy consumption of farm; transportation, and ii) processing of products from “farm-gate” to “grave”, including transport animal to the slaughterhouse, product processing, packaging and other related links to consumers caused by GHGs (FAO, 2011). Our study included the process from “cradle” to “farm-gate”. The mean CO_2-eq for pig production in Beijing per kg carcass was 3.7 kg in 2014, which was lower than that of EU (4.5–7.5 kg) and North America (4.7 kg) (Weiss and Leip, 2012; Gerber et al., 2013). The mean CO_2-eq for dairy production in Beijing per kg liquid milk was 1.3 kg in 2014 which was lower than the average CO_2-eq in global (2.4 kg), North America (1.8 kg), China (1.5 kg) and EU (0.6–1.5 kg) (Weiss and Leip, 2012), and higher than that of US (0.7 kg) and Germany (0.9 kg) (Reinhardt et al., 2009). The mean CO_2-eq for beef cattle production in Beijing, per kg beef, was 14.4 kg in 2014 which was lower than the average CO_2-eq in EU (18.2–22.2 kg) and North America (29 kg) (Gerber et al., 2013; Weiss and Leip, 2012), and higher than that of China (10.2 kg) (Ma et al., 2010) and Canada (10.4 kg) (Vergé et al., 2008). The mean CO_2-eq for layer production in Beijing per kg eggs was 1.4 kg in 2014 which was lower than the average CO_2-eq in EU (1.6–2.9 kg) (Weiss and Leip, 2012), US (1.5 kg) (Pelletier et al., 2013) and North America (2.9 kg) (Gerber et al., 2013). The mean CO_2-eq for sheep production in Beijing per kg meat was 25.2 kg in 2014 which was higher than that of EU (16.6–20.3 kg) and UK (15 kg) (Weiss and Leip, 2012; Williams et al., 2006).

The division of the system boundary is an important part in the gas loss assessment, and the system boundary directly affects the uncertainty of the final results (FAO, 2011). The system boundary in most of these previous studies was from “cradle” to “farm-gate”, but some components were not considered, e.g. land spreading emissions, which result in lower product footprints (Bellarby et al., 2013). The other main reason resulting in different GHGs emission footprints were manure type. The method of manure collection from the animal house in China is the ‘gan qing fen’ system (Huaitalla et al., 2010; Schuchardt et al., 2011), literally translated as ‘clear manure dryly’, which separates the solid and liquid manure fractions in-house. This system is different to most housing systems in the EU, where slurry-based systems dominate intensive livestock farms. This type of slurry-based system provides an anaerobic environment which leads to greater CH_4 emissions (Sommer et al., 2009), and little/no N_2O emissions until the slurry is spread on the land. Urban livestock production in Beijing is dominated by industrial systems, and their impact on the environment depends both on livestock species and on the processing of the inputs (feed supply) and the outputs (animal products). The other reasons causing the difference of GHGs emission was product yield. For instance, the mean milk yield in Beijing was 7600 kg head^{-1} which was lower than that of EU average (8000 kg head^{-1}), US (9337 kg head^{-1}) and Japan (8000 kg head^{-1}), and higher than the average yield for China (Li, 2013).

4.2. Mitigation potential of livestock production

The results indicate that improved livestock diet and manure management in urban livestock production systems have an influence on GHGs and NH_3 emissions. CH_4 emission depends greatly on the level of feed intake; the quantity of energy consumed, and feed composition (Giger-Reverdin et al., 2003). Methane from enteric fermentation is controlled by three key factors, such as rate of organic matter (OM) fermentation, type of volatile fatty acids (VFA) produced, and efficiency of microbial biosynthesis. A theoretical study demonstrated that CH_4 production was reduced from 6.6 to 6.0% of the gross energy (GE) consumption by dairy cows when the dry matter intake of a 1:1-ratio of grass silage and concentrate diet was increased from 10 to 24 kg per day (Mills et al., 2001). Reducing animal numbers whilst increasing average yield per animal has a great potential to decrease GHGs emission per unit product (Cederberg et al., 2009), as seen in the scenario analysis.

GHGs and NH_3 emissions occur throughout the whole manure management chain including housing, storage and treatment (Chadwick et al., 2015). During storage, microbial activity results in the production and loss of CO_2, CH_4, N_2O and NH_3, the magnitude of which depends on the origin of the manure and the storage conditions (Petersen et al., 1998, 2013). The range of approaches to manage CH_4 and N_2O emissions from animal manure stores include anaerobic digestion, composting, cooling storage tanks, compaction and covering solid manure/compost heaps (Tubiello and Loudjani, 2010). In our study, we chose current mitigation technologies used in Beijing livestock production (mitigation of emissions from soils, CH_4 from enteric fermentation, and CH_4, CO_2 and N_2O from manure management and energy consumption). GHGs emission from manure management (not including land spreading) could be reduced by 10% through wide-scale adoption of anaerobic digestion, more in line with emission standards. Composting has been recommended to improve manure quality, but this does not alleviate the problem of the GHGs and NH_3 emission (Hao et al., 2001). This is the main reason for the low GHGs emission reduction potential of scenario three (S3) in poultry production. Meanwhile, technical mitigation options for GHGs mitigation from livestock systems are often more economical at a larger scale for the farmer. This is the reason why the larger farm had the lowest CH_4 emission per kg animal product from enteric fermentation, and CH_4, CO_2 and N_2O from manure management, but highest CH_4, CO_2 and N_2O emission per kg animal product from energy consumption. These technical solutions need to be seen alongside changes in the production system: e.g. biogas installation would favor farms with high animal numbers and indoor production systems that could have other detrimental implications, such as animal welfare (Sommer et al., 2009).

4.3. Policy implications for livestock production

With the increase in human population and demand for livestock products, as well as the development of urbanization in China, the development of livestock production in peri-urban areas has changed greatly. The reason for this change is mainly from the regional livestock policies and environmental regulations of Beijing government.

The division of urban functional areas has resulted in changes to the numbers and structure of livestock farms in various regions which were originally hotspots of gaseous emissions. Beijing is divided into four functional areas: the core area of city, an urban expansion area, the new urban development area, and the ecological conservation area (BMBCA, 2003). During the 12th Five-Year plan (2011–2015), the city of Beijing proposed the establishment of prohibited areas, restricted areas and sustainable development zones, which resulted in the strategic shift of livestock production from the inner suburbs to the outer suburbs of the city. However, even if the basic principle of the municipal government on livestock distribution is correct, there have been some deviations at the county and township government level in the implementation of the municipal government policy. For example, the Miyun government, located in water conservation in Beijing City, has proposed to become the “Livestock County”, which is direct conflict with protection of the local natural environment before 2010. Encouragement for livestock farm size in this county is the reason that the most obvious GHGs and NH_3 emission hotspots

are the Yanqing, Miyun and Pinggu Districts, which all belong to the ecological conservation area.

The Beijing municipal government has also introduced a policy to change the structure of the traditional livestock breeding program from grain consuming livestock (pig, layer and broiler production) to grain saving livestock (beef cattle, dairy cattle and sheep) due to the conflict of growing grain crops for human and livestock consumption. However, since most of these grain saving livestock are ruminants, GHG emissions are likely to increase. Nevertheless, it is interesting that because of human consumption preference, pig, layer and boiler products are still the main products in the current supply market of Beijing (BMCRA, 2011). This is counter to the goals of government policy implementation. This is the inevitable result of the trade-off between the limited urban agricultural resources, environmental protection and market demand.

Modern urban agricultural development planning in Beijing during the "12th Five-Year plan" (2011–2015) period required that the self-sufficiency rate of poultry, eggs, milk and pork should reach 70%, 66%, 68% and 30%, respectively (BMCRA et al., 2012). This will need urban livestock production to reduce its environmental impact while ensuring supply. Therefore, many of the policies, regulations and environmental standards were introduced gradually, so that the manure utilization rate of urban industrial livestock farms can reach more than 90% and to meet zero emission goals (BMCRA et al., 2012). However, the present financial subsidy for manure treatment technology only provides a one off grant, related to the construction process of emission reduction facilities, while the implementation of GHG and NH_3 emission reduction is a long-term process, requiring continuous monitoring. Therefore, the utilization rate of biogas facilities in many industrial farms is not very high, and the emission reduction targets have not been implemented in accordance with the planning and policy requirements.

5. Conclusion

Our study, for the first time, provides comprehensive gaseous emission inventories for CH_4, CO_2, N_2O and NH_3 from livestock production in the peri-urban area of Beijing. We also quantified the impact of changes in intensification rate, optimizing livestock diet and manure management on the reduction of GHGs and NH_3 emissions.

Overall, farm numbers were positively correlated to the increase in animal numbers. However, compared to 2010, farm size only increased for large livestock systems (cattle, pigs and sheep), but decreased for poultry in 2014. This implies that current policies and regulations were not very effective for the new and expanded livestock farms. Despite this, the total GHGs emission from all livestock products decreased from 5.0 Tg CO_2-eq in 2010 to 4.5 Tg CO_2-eq in 2014. The total NH_3 emission of all livestock products decreased from 102 Gg in 2010 to 96 Gg in 2014. This suggests that the relevant environmental policies and regulations had some positive effects in reducing GHGs and NH_3 emissions in peri-urban livestock production.

Of all the GHGs, CO_2 emission represented the largest contribution to total emissions, as a result of energy requirements for cooling animal housing. Total GHGs emissions were mainly contributed by broiler and pig farms, while the distribution of pigs and sheep were responsible for NH_3 emissions. CH_4 and NH_3 emission were negatively related to farm size because more effective manure treatment was adopted on industrial farms, while N_2O and CO_2 emissions were positively related to farm size. Overall, the GHGs and NH_3 emissions hotpots across the peri-urban landscape, but hotspots have transferred from suburban areas to exurban areas in 2014 compared with 2010. Pig, dairy and broiler enterprises are the emission hotspots across the peri-urban area.

Our scenario analysis suggests that the total GHGs emission can be reduced up to 1.0 Tg CO_2-eq, by 23% of total livestock sector emissions in Beijing, depending on mitigation strategies. The integrated scenario which combined improved intensification rate, livestock diet and manure management showed the greatest potential in CH_4, N_2O and NH_3 reduction, by 27%, 9% and 35%, respectively, compared to the BAU scenario. The insights from our study can provide guidance for defining and prioritising mitigation strategies to reduce GHGs and NH_3 emission in other rapidly developing cities and countries.

Notes

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.12.257.

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